Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 90 (1997)

Heft: 1

Artikel: High-precision U-Pb and 40Ar/39Ar dating of an Alpine ophiolite (Gets nappe, French Alps)

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DOI: https://doi.org/10.5169/seals-168144

Eclogae geol. Helv. 90 (1997) 43–54
0012-9402/97/010043-12 $1.50 + 0.20/0

Eclogae Geologicae Helvetiae

High-precision U-Pb and $^{40}Ar/^{39}Ar$ dating of an Alpine ophiolite (Gets nappe, French Alps)

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Key words: Ophiolites, U-Pb and $^{40}Ar/^{39}Ar$ geochronology, Prealps, Alps, Tethys

ABSTRACT

Coarse-grained gabbros from two different localities in the Gets nappe (Upper Prealps) have been dated by U-Pb and $^{40}Ar/^{39}Ar$ isotopic analyses. Zircons from both gabbros gave identical concordant U-Pb ages of 166 ± 1 Ma (Fig. 4). Amphibole from one of them gave an $^{40}Ar/^{39}Ar$ plateau age of 165.9 ± 2.2 Ma (Fig. 5). This concordance implies that 166 ± 1 Ma is the age of magmatic crystallization of these gabbros.

The Gets wildflysch with its mafic and ultramafic lenses is an ophiolitic mélange, that we infer to come from a proximal part of the accretionary prism at the foot of the active SE margin of the Piemont ocean. In this position we can expect to find remnants of the oldest parts of the Piemont oceanic crust.

These are the first high-precision dates using modern techniques from an Alpine ophiolite and are in excellent agreement with the following:

1) The few, somewhat younger, reliable ages on ophiolites from the probable continuation of the Piemont basin into the Apennines and Corsica;

2) Recent data on the age of the first supra-ophiolitic sediments (Late Bathonian to Early Callovian radiolarites);

3) The structural and stratigraphic evolution of the Briançonnais (s.s.) domain, the future NW margin of the Piemont ocean. We note a remarkable coincidence, in Late Bajocian time, between: (A) the end of tensile fracturing in the Briançonnais continental crust; (B) the beginning of its subsidence; (C) the age of the Gets ophiolites. This coincidence is consistent with an ocean opening mechanism based on a combination of subhorizontal extension and thermally driven vertical movements of the lithosphere.

RESUME

Des gabbros de deux localités différentes de la nappe des Gets (Préalpes supérieures) ont été datés par les méthodes isotopiques U-Pb sur zircon et $^{40}Ar/^{39}Ar$ sur amphibole. Les zircons des deux gabbros ont donné des âges U-Pb identiques et concordants de 166 ± 1 Ma (fig. 4). L'amphibole de l'un d'eux a donné un âge plateau $^{40}Ar/^{39}Ar$ de 165.9 ± 2.2 Ma (fig. 5). Cette concordance démontre que 166 ± 1 Ma est l'âge de leur cristallisation magmatique.

Nous interprétons le wildflysch à lentilles mafiques et ultramafiques de la nappe des Gets comme un mélange ophiolitique qui provient d'une partie proximale du prisme d'accrétion, au pied de la marge active SE de l'océan Piémontais. On peut donc s'attendre à y trouver des témoins des roches les plus anciennes de la croûte océanique Piémontaise.

Cette première datation d'une ophiolite alpine par des méthodes modernes est en excellent accord avec:

1) Les rares âges fiables (un peu plus jeunes) obtenus à ce jour sur des ophiolites de la continuation probable du bassin piémontais dans les Apennins et en Corse;

2) Les données récentes sur l'âge des premiers sédiments supra-ophiolitiques (radiolarites du Bathonien sup. – Callovien inf.).

3) L'évolution structurale et stratigraphique du domaine Briançonnais s. str., future marge NW de l'océan Piémontais. On note une coïncidence remarquable, au Bajocien supérieur, entre: (A) la fin de la tectonique d'extension dans la croûte continentale Briançonnaise; (B) le début de sa subsidence; (C) l'âge des ophiolites de la nappe des Gets. Cette coïncidence est en accord avec un mécanisme d'ouverture océanique basé sur une combinaison d'extension subhorizontale et de mouvements lithosphériques verticaux d'origine thermique.

1. Introduction

Ophiolites, relics of oceanic lithosphere, are keystones for reconstructing the location and history of former oceans in orogenic belts. They provide the only direct evidence for dating the formation of old oceanic crust.

But dating the crystallization of ophiolitic rocks is a notoriously difficult task, because of their very low content in radioactive elements, and because their tectonic position usually predestines them to alteration, metamorphism and partial or complete resetting of the radiogenic clocks. In many orogenic belts, precise dating of ophiolites remains a challenge.

The aim of this paper is to provide the first high precision geochronologic age of an ophiolite in the Alps. We present U/Pb zircon and $^{40}Ar/^{39}Ar$ hornblende data from coarse-grained ophiolitic gabbros sampled in a nappe that was tectonically expelled out of the closing ocean at an early stage of the orogeny and therefore escaped any significant metamorphism.

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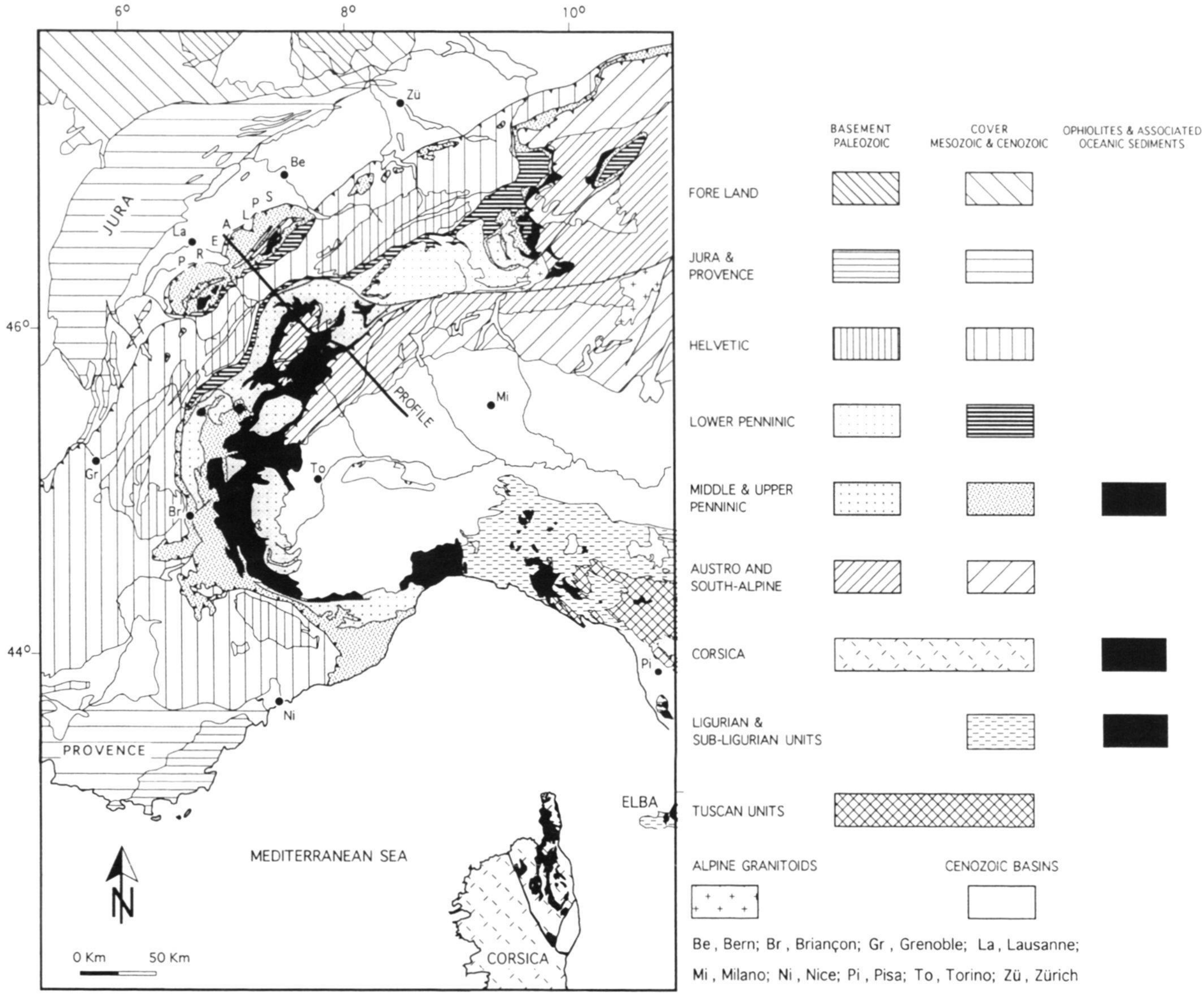


Fig. 1. Simplified tectonic map of the western Alps, Corsica and northern Appennines (modified from Escher et al. 1988 and Bigi et al. 1990).

2. Ophiolites in the western Alps

In the Alps, ophiolites are present in several distinct tectonic zones (Fig. 1) and it remains a matter of controversy if all these zones originated from a unique ocean disrupted by tectonics, or if there were two or more oceans perhaps of different age and history. Various models of Alpine paleogeography coexist in the recent literature (e.g. depending on the assumed status of the Valais domain, the Monte Rosa nappe or the Canavese zone). We will not discuss them here, as a general evaluation of all these models would be beyond of the scope of this paper, and we shall base the interpretation of our data on one possible reconstruction whose main features are reasonably founded and generally accepted. In particular most palinspastic restorations agree that at least a majority of the ophiolites from the western Alps belong to the *Piemont* basin and that this basin was a major branch of the Tethys ocean in the Alpine system during the Mesozoic (e.g. Elter 1971, Lemoine 1972 and 1983, Dal Piaz 1974a, Bernoulli & Lemoine 1980, Trümpy 1980, Beccaluva et al. 1984, Lagabrielle 1987, Stampfli 1993, Martin et al. 1994).

On a cross-section through the western Swiss Alps and neighbouring regions of Italy and France (Escher et al. 1988 and 1993), ophiolites of presumed Piemont origin occur in four tectonic positions (Fig. 2):

1 and 2. – The *Zermatt – Saas* and *Antrona* zones: These contain the whole range of ophiolitic rocks (ultramafic and mafic plutonic rocks, dykes and volcanic rocks) associated with minor amounts of oceanic sediments. They have been affected during eoalpine subduction by a high-P (eclogite facies) metamorphism, followed by a greenschist or amphibolite grade

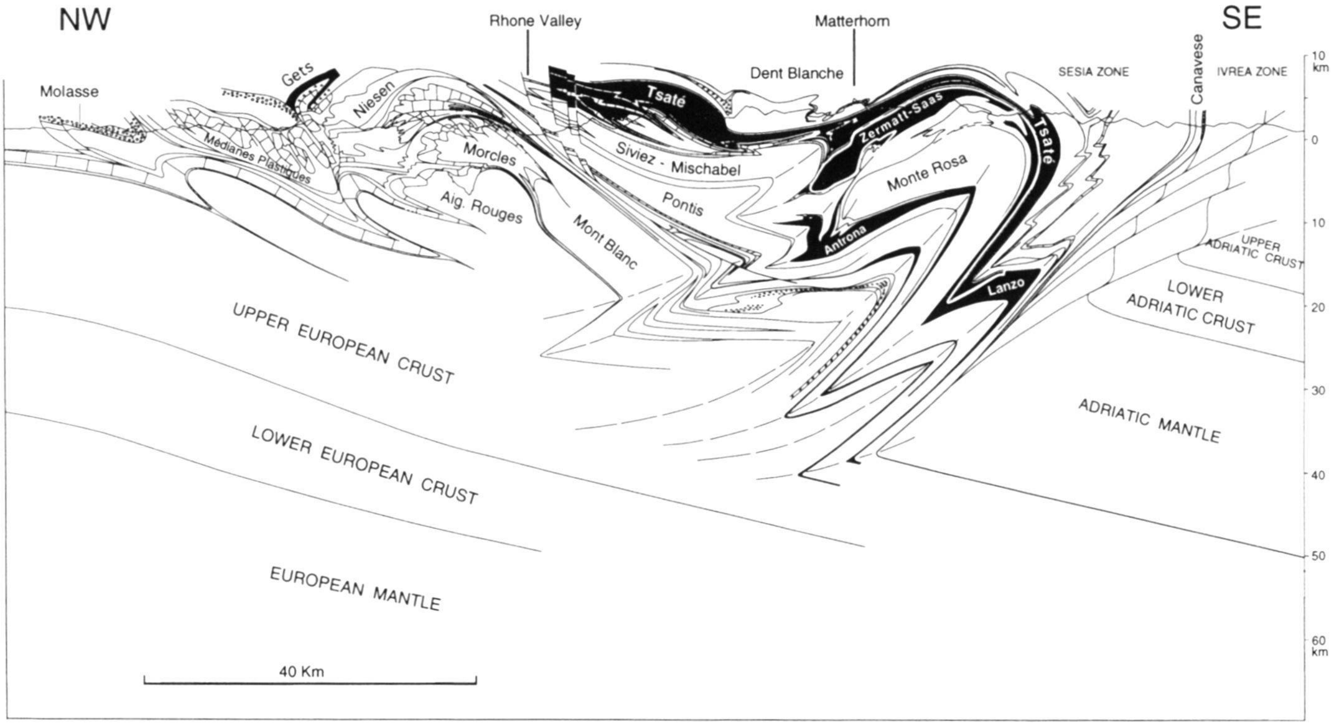


Fig. 2. Tectonic cross-section through the western Swiss Alps. Black: ophiolitic nappes (modified from Escher et al. 1993 and in press).

metamorphism of Tertiary age (e.g. Bearth 1974, Dal Piaz 1974b, Hunziker 1974, Dal Piaz & Ernst 1978, Colombi 1989, Pfeifer et al. 1989, Steck 1989, Vannay & Allemann 1990).

3. – The *Tsaté* nappe (middle and upper parts of the former Combin zone of Argand 1909; Escher et al. 1988, Sartori 1987): Here the ophiolites form slices and lenses imbricated with calcschists (the "schistes lustrés"). Most of these schists represent a flysch sedimentation, sometimes chaotic, of late Cretaceous age (Marthaler 1984). The Tsaté nappe rests at the top of the Penninic pile of nappes and is only affected by low-grade blueschist to greenschist facies metamorphism (e.g. Kienast 1973, Dal Piaz 1976, Baldelli et al. 1983, Kunz 1988, Sperlich 1988, Vannay & Allemann 1990, Ballèvre & Merle 1993). Its imbricated structure, the dislocation of the ophiolitic bodies, their concentration at the top of the nappe, and the syntectonic turbiditic or chaotic sedimentation have been interpreted as characteristic of an accretionary prism (Marthaler & Stampfli 1989).

4. – The *Gets* nappe: It belongs to the Prealps, a thick pile of decollement cover nappes that have been expelled out of their Penninic homeland at an early stage of the Tertiary continental collision and thrusted onto the foreland of the belt. Because of this early displacement, these nappes escaped most of the metamorphism and deformation that affected the Penninic domain and offer exceptionally good conditions for geochemical investigations of the pre-collisional history of the belt. The Gets nappe rests at the top of this pile (Caron 1972). It consists of a sequence of late Cretaceous flysch overlying a composite and partly chaotic basal formation (wildflysch) with abundant blocks and lenses of ophiolites (basalts and diabases, serpentinites and more rarely gabbros), deep-water sediments (radiolarites, pelagic limestones, manganesiferous shales) and Paleozoic granites imbedded in a black pelitic matrix (Fig. 3). It is affected by a very weak metamorphism (illite "cristallinity" in the anchizone, Caron & Weidmann 1967).

This complex is a typical *ophiolitic mélange* in the sense of Gansser (1974), a rock association that plays a prominent role in several Tethyan belts where it is always related to oceanic sutures and convergent plate boundaries. By its high tectonic position and its composite internal structure it offers some similarities with the Tsaté nappe, but its homeland probably was closer to the continent which provided the blocks of granitic crust. It may be interpreted as a relatively shallow part of the accretionary prism, originally situated near the foot of the southern active margin and precociously exhumed and thrusted over the European margin.

3. Age of the Piemont ophiolites: present state of knowledge

3.a Earlier attempts of isotopic dating

Two attempts of dating Piemont ophiolites by isotopic methods can be mentioned:

- In the Gets nappe: Whole rocks and hornblendes from gabbroic to basaltic ophiolites have been dated by K/Ar

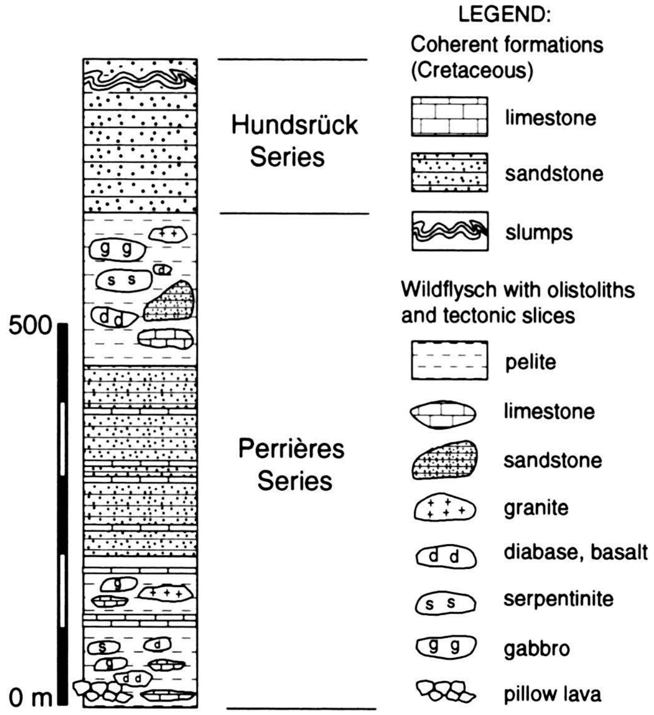


Fig. 3. Simplified stratigraphic section of the Gets nappe (modified from Caron & Weidmann 1967, Caron 1972 and Flück 1973).

and $^{40}Ar/^{39}Ar$ (whole rock total fusion) methods (Bertrand 1970, Bertrand & Delaloye 1976, Fontignie et al. 1982). This pioneering work gave a very broad scattering of data between 193 and 63 Ma, with a best fit average K/Ar age of 180 ± 29 Ma for ten hornblende samples. The interpretation of this large span of time is uncertain.

- In the Cottian Alps (150 km SSW of the Zermatt – Gets cross-section): Carpena & Caby (1984) published fission track ages of five zircons from plutonic ophiolites, most of which are affected by a blueschist facies metamorphism. These ages range between 212 and 192 Ma, and the authors conclude that spreading of the Piemont ocean took place from Late Triassic to Middle Jurassic. Although widely quoted, these data must be considered suspect. It is difficult to believe that fission tracks survived without any resetting through a blueschist grade thermal event, even brief as these authors suggest.

Outside the Alps, the Piemont basin is generally considered to extend southward into the Ligurian basin of the northern Apennines, whose ophiolitic bodies are similar to those of the Penninic nappes. Some flysch units of the external Ligurides also present a structure and content nearly identical to the Gets nappe (Elter et al. 1966, G. V. Dal Piaz pers. comm.). Ophiolitic gabbros from the Ligurian basin have been dated by zircon fission tracks between 185 ± 23 Ma and 161 ± 23 Ma (Bigazzi et al. 1972 and 1973). But these ages, also frequently quoted, were calculated with an old value of the constant λ_f (Bigazzi & Ferrara 1971). Moreover the tracks were measured on the external surfaces of the grains, which casts doubt on the significance of these data. Certainly more reliable are the $^{40}Ar/^{39}Ar$ ages of amphiboles from two ophiolitic diorites from the same area (Bortolotti et al. 1990). In spite of the presence of some excess argon, they gave relatively good plateau dates at 152 ± 2 Ma, recently recalibrated as 158.3 ± 1.5 Ma (Bortolotti et al. 1995). These authors also published four plateau ages between 157.2 ± 0.5 and 158.6 ± 1.1 Ma on hornblendes from ophiolitic plagiogranites. These dates can be interpreted as the age of magmatic emplacement or of an immediately subsequent oceanic metamorphism. On the contrary, $^{40}Ar/^{39}Ar$ ages on plagioclase from basaltic dykes are completely discordant and meaningless (Bortolotti et al. 1991). Still in the northern Apennines, zircons from plagiogranites sampled in three different Ligurian ophiolitic units (Voltri group, Sestri-Voltaggio zone and Bracco zone) gave discordant U-Pb ages with most analytical points concentrated near the lower intercept around 150 Ma. This date can be interpreted as a minimum crystallization age (Borsi 1995). The same author published a whole-rock Sm/Nd age of 177 ± 23 Ma on eclogitic metagabbros from the Voltri group.

Still farther, in Corsica, ophiolites gave ages of 181.4 ± 6 Ma (K/Ar on amphibole in a metagabbro, Beccaluva et al. 1981) and 161 ± 3 Ma (U-Pb on zircon in two albitites, Ohnenstetter et al. 1981). The latter result seems to be one of the most reliable of all the presently available isotopic ages on Tethyan ophiolites from the northwestern Mediterranean region. Its extension to the Piemont ophiolites depends on the choice of a palinspastic model of correlating the oceanic basins between the different segments of the Alpine system in this region, a highly controversial question (e.g. Lagabrielle 1987).

Toward the East, a probable continuation of the Piemont ophiolites is to be found in the Arosa zone (200 km East of the Zermatt – Gets cross-section), whose tectonic position and structure are similar to the Gets nappe. There, in the large Totalp ultramafic body, phlogopite from a pyroxenite gave a $^{40}Ar/^{39}Ar$ age of 160 ± 8 Ma (Peters & Stettler 1987). This is a cooling age that the authors interpret as an age of upwelling of subcontinental mantle, an event that would also be related to the opening of the oceanic basin. This interpretation is in agreement with sedimentological observations that reveal the early appearance of large areas of ultramafic rocks on the bottom of the incipient Piemont ocean (e.g. Baldelli et al. 1983, Tricart & Lemoine 1983, Lemoine et al. 1986, Caby et al. 1987, Lagabrielle 1987).

3.b Stratigraphic constraints: age of the first post-ophiolitic sediments

Sediments directly overlying the Piemont ophiolites, often radiolarites, place a younger limit on their age. Radiolaria are remarkably well preserved at a few places in the Cottian Alps in undeformed spherolites of rhodochrosite (St-Véran) or in phosphatic nodules (Traversiera) in spite of strong regional deformation and blueschist facies metamorphism (De Wever & Caby 1981, Schaaf et al. 1985, Lagabrielle 1987). Their biochronological significance has recently been reassessed (De Wever & Baumgartner 1995). Their age is Late Bathonian to Early Callovian (late Middle Jurassic) at Traversiera, and Middle to Late Oxfordian (early Late Jurassic) at St-Véran. The supra-ophiolitic radiolarites are thus diachronous.

Outside the Alps, the supra-ophiolitic radiolarites from the northern Apennines, Elba and Corsica give similar results (Baumgartner 1984, Bortolotti et al. 1995, Marcucci & Conti 1995, De Wever & Danelian 1995). Their base is never older than Late Bathonian – Early Callovian, and may be as young as Late Oxfordian – Early Kimmeridgian.

3.c *Indirect dating of the Piemont ocean opening by its tectono-erosive effects on its margins*

Triassic Alpine paleogeography shows no hint of the existence of a Piemont ocean. Its birth is obviously related to the pronounced paleogeographic differentiation of the Alpine system during the Early (Liassic) and Middle Jurassic (Dogger) epochs. Crucial information about this event is recorded in the structure and stratigraphy of its margins, especially the NW (European) margin whose large sectors are well preserved (e.g. in the Prealps, that we will more particularly consider in the following). This margin is characterized prior to the mid Jurassic by an important uplift (causing the erosion of > 1 km of Triassic and Liassic sediments) combined with vigorous extensional tectonics, a combination typical of the lateral swelling or doming of a rift (Baud & Masson 1975). This uplift and the subsequent subsidence, revealed by the unconformable transgression of Late Dogger or Malm platform sediments on the eroded rise, defines the Briançonnais *(sensu stricto)* domain (Trümpy 1960, Baud 1972). The detailed chronology is reasonably well constrained by the biostratigraphy:

- The onset of the Briançonnais (s.s.) uplift is not precisely determined: Middle Liassic according to Badoux & Mercanton (1962), Early Dogger according to Septfontaine (1983) or Late Liassic following Septfontaine (1995). The reason of this uncertainty lies in the partial destruction of the stratigraphic record by the ensueing erosion.
- In any case the maximum NW extension of the emerged Briançonnais (s.s.) land is reached during Middle Bajocian (late Early Dogger; Septfontaine 1983).
- During this time span continuous uplift and simultaneous NW-SE extension are demonstrated by: (1) the increasingly deep erosion of Triassic layers from NW to SE (Mégard-Galli & Baud 1977); (2) the Liassic to Dogger movement of large normal faults which control erosion, unconformities and the local deposition of continental to shallow water sediments at the NW foot of the rise (e.g. Sartori 1990, Hürlimann et al. 1996); (3) an ubiquitous system of small scale conjugate faults and tension fractures closely associated with synkinematic underground paleokarstic cavities (Baud & Masson 1975). These cavities establish a link between the structural and the stratigraphic evolution of the Briançonnais rise. The age of the karstic sediments is poorly constrained and may span Late Liassic to Dogger, but their mineralogy often reveals a mixing of marine and fresh waters which points to a filling of the karst during the earliest stage of the marine transgression (Baud et al. 1979). The mid Jurassic transgression "froze" the karst and the associated system of fractures while in full activity.
- Extension suddenly stops at this time, as revealed by the fact that the tension fractures never affect the Late Dogger and Malm transgressive layers. Thus the onset of subsidence coincides with an abrupt change in the stress state of the Briançonnais crust. We ascribe this dynamic change to the opening of the neighbouring ocean: the break-off of the crust causes the relief of the deviatoric stress in the continental margins, rapidly followed by their thermal subsidence. In this interpretation the age of the beginning of the transgression is crucial for indirectly dating the birth of the Piemont ocean.
- The base of the transgression is dated as Late Bajocian – Early Bathonian (mid Dogger) by classical macropaleontological data (De Loriol & Schardt 1883), by ostracoda (Page 1969) and by benthic foraminifera as well as by detailed lithostratigraphic correlations (Furrer 1977, Septfontaine 1983).

In the Briançon type area (150 km SSW of the Prealps) the timing is not quite so tightly constrained but the stratigraphical and structural evolution is essentially similar (e.g. Mercier 1977, Tricart et al. 1988, Faure & Megard-Galli 1988).

3.d *Age of Piemont ophiolites: an unresolved question*

In conclusion, no precise and reliable isotopic ages are presently available for the generation of oceanic crust now preserved in Alpine ophiolites (Hunziker et al. 1992). The best clue to the birth of the Piemont ocean is provided by the structural and stratigraphic evolution of its NW margin (the Briançonnais s.s. rise). It points to an opening age close to (and probably slightly older than) the Bajocian – Bathonian limit (164 ± 2 Ma according to Odin 1994), nearly exactly in the middle of the Jurassic period. This conclusion is in agreement with the Late Bathonian age of the earliest known supra-ophiolitic radiolarites.

However this conclusion is only an inference based on a tentative geodynamic interpretation of geological data from outside the Piemont itself. The absence of isotopic ages on ophiolites by modern methods certainly is a major shortcoming of Alpine geology. Here we present $^{40}Ar/^{39}Ar$ hornblende and U-Pb zircon ages of two gabbro lenses from the Gets nappe.

Tab. 1. Chemical composition of the Getts gabbros. Rock samples analysed with XRF, minerals with microbe.

Major elements (in Wt %)	Rock samples	
	RB3	MR3
SiO_2	52.21	47.59
TiO_2	0.70	3.02
Al_2O_3	20.14	15.54
Fe_2O_3	4.22	10.26
MnO	0.10	0.16
MgO	7.20	8.63
CaO	4.94	5.68
Na_2O	4.82	5.04
K_2O	1.78	0.36
P_2O_5	0.06	0.06
H_2O+CO_2	2.99	2.82
TOTAL	99.16	99.16

Trace elements (in ppm)	Rock samples	
	RB3	MR3
Ba	955	478
Ce	< 6	34
Co	27	45
Cr	174	81
Cu	< 4	47
Ga	7	12
Hf	< 2	3
La	< 4	16
Nb	< 5	33
Nd	< 3	29
Ni	74	204
Pb	< 2	< 2
Rb	66	6
S	37	40
Sr	613	297
Th	< 1	< 1
U	< 2	< 2
V	114	324
Y	7	50
Zn	30	75
Zr	50	276

Elements (in Wt %)	Minerals		
	RB3		MR3
	Clinopyroxene	Amphibole	Amphibole
SiO_2	49.96	40.52	41.77
TiO_2	1.51	3.99	3.55
Al_2O_3	4.55	13.46	10.66
FeO tot	6.76	9.84	13.49
MnO	0.21	0.14	0.27
MgO	13.08	13.50	12.30
CaO	22.48	11.82	11.38
Na_2O	0.81	3.13	3.17
K_2O	-.-	0.79	0.82
Cr_2O_3	0.15	0.00	0.03
F	-.-	0.09	0.08
Cl	-.-	< 0.01	< 0.01
TOTAL	99.51	97.28	97.52

4. Sampling

4.a Sampling location

Coarse-grained to pegmatitic gabbros, probably representing late stages of magmatic crystallization, are the best candidates for hosting zircons. Such rocks were found as large lenses in the basal wildflysch of the Gets nappe (Perrières series) at two localities in the French Prealps near the Col des Gets: the *Mouille Ronde* (sample MR3, topographic coordinates: 6°41'06"/46°08'18") and the *Ruisseau des Bounaz* (sample RB3, 6°38'04"/ 46°07'31"). For detailed field descriptions and stratigraphic or petrographic studies of the wildflysch and its various lenses, see Jaffé (1955), Caron & Weidmann (1967) and Bertrand (1970).

4.b Sample characteristics

Sample MR3 is a pegmatitic gabbro with cm-long crystals of milky plagioclase (60 vol. %) and amphibole. The rock records a strong shearing characterized by a preferred mineral orientation and the deformation and partial granulation of plagioclase which recrystallized synkinematically into small polygonal grains. The euhedral pale-green to brownish amphibole is a Ti-rich ferroan pargasite (Tab. 1), which mostly survived the deformation, except in a few shear bands in which it broke down into small angular grains of identical composition. A retrograde, low-temperature assemblage of chlorite + sphene is systematically developing along the cleavage planes of the mineral. The pargasitic composition of the amphibole as well as its high Ti content (0.4 per formula unit), typically point to a magmatic, possibly late-magmatic/deuteric origin (e.g. Raase 1974, Girardeau & Mevel 1982). Moreover, the large size and the euhedral shape of the crystals (up to 5 cm), the absence of pyroxene relics, chemical zoning and the pegmatitic nature of the rock all suggest that this ferroan pargasite directly crystallized from a rather evolved, hydrous melt. Plagioclase porphyroclasts and recrystallized grains are completely sericitised, which does not allow any inference on the metamorphic conditions at the time of dynamic recrystallization. Nevertheless, the fact that the magmatic amphibole survived this deformational event leads us to believe that most of the recorded deformation occurred just after the gabbro solidification, during an early stage of intraoceanic tectonics.

Sample RB3 is a coarse-grained, undeformed gabbro with a sub-ophitic texture. The dominant ferromagnesian mineral is a Ti-bearing augitic clinopyroxene (Tab. 1). In places, it is rimmed by a brown, high-Ti pargasite (Tab. 1), and includes a few resorbed, altered olivine crystals. The plagioclase is euhedral and sericitised.

The chemical composition of both gabbros is reported in Table 1. The two samples have a different chemical composition. MR3 gabbro with 5.4% alkalies plots in the field of alkaline gabbros with normative olivine and nepheline. The high TiO_2 and Fe_2O_3 abundance and a relatively low Al_2O_3 and CaO content show the high modal proportion of titaniferous pargasitic amphibole. Sample RB3 has 52.2% SiO_2 and 6.6% alkalies, placing it in the field of olivine gabbros. RB3 has normative olivine and hypersthene. Its high Al_2O_3 content is reflected by a small amount of normative corundum (1.5%). However, the rock is not peraluminous; it just reflects a high proportion of calcic plagioclase. Fe_2O_3 is rather low considering the basaltic nature of the rock. A spider plot normalized to MORB (not represented here), shows curves enriched in incompatible elements. The MR3 gabbro also shows a concave aspect for the incompatible elements linked with a weak amount of potassium, probably corresponding to partial leaching. The chemical composition of these rocks show transitional geochemical characteristics for RB3, whereas they are clearly alkaline for MR3.

Tab. 2. U-Pb isotopic data for zircons from gabbros MR3 and RB3. See text for sample descriptions and zircon characteristics. *: radiogenic; **a:** in mole-% relative to total radiogenic Pb; **b:** corrected for spike Pb and for fractionation; **c:** corrected for fractionation, spike, U and Pb blanks, and initial common Pb when present, error estimates (95% confidence level) refer to the last significant digits of the isotopic radios and reflect reproducibility of standards, measurement errors and uncertainties in the common Pb correction.

#	Mass	Concentrations			Atomic ratios				Apparent ages (Ma)		
		U	Pb*	208Pb*	206/204	206/238	207/235	207/206	6/38	7/35	7/6
	mg	ppm		a	b	c	c	c			
MR3 gabbro											
(1)	.049	121	3	14	4871	.02608±12	.1777±10	.04941±12	166.0	166.1	167.3
(2)	.075	125	4	16	8313	.02605±12	.1776±10	.04943±10	165.8	166.0	168.3
(3)	.054	295	9	27	22149	.02605±12	.1781±10	.04957±8	165.8	166.4	175.1
RB3 gabbro											
(4)	.018	58	2	17	375	.02613±12	.1781±22	.04944±50	166.3	166.4	168.7
(5)	.029	59	2	15	2762	.02605±14	.1774±12	.04941±20	165.8	165.9	167.3
(6)	.013	77	3	15	2526	.03755±18	.2753±16	.05317±18	237.6	246.9	335.9

5. Isotopic analyses

5.a Analytical procedures

U-Pb zircon analysis

Zircons were isolated using standard heavy liquid and magnetic techniques. Air abrasion was applied extensively in order to increase the degree of concordancy of the ages (Krogh 1982). Chemistry was carried out according to the standard procedure developed at the Royal Ontario Museum (Krogh 1973), using minibombs, small separation columns and a mixed ^{205}Pb–^{235}U spike. Isotopic measurements were made on a VG354 mass spectrometer in single collector mode. Pb and U were loaded together with silica gel and H_3PO_4 on Re-filaments. A conversion factor of 0.37% per atomic mass unit (AMU) was applied to data obtained by the Daly photomultiplier detection system. Pb and U analyses were corrected for a fractionation of +0.1%/AMU (Corfu & Grunski 1987) and for blanks of less than 2 picograms (Pb isotopic composition: $^{208}Pb : ^{207}Pb : ^{206}Pb : ^{204}Pb$ = 37.62 : 15.56 : 18.3 : 1). Error calculations were computed using the (unpublished) ROMAGE 4.1 program, developed at the Royal Ontario Museum by J. Connely and L. Heaman. Decay constants are those recommended by Steiger & Jäger (1978). Quoted errors are given at the 95% confidence level.

$^{40}Ar/^{39}Ar$ amphibole analysis

The $^{40}Ar/^{39}Ar$ analyses were made at the Université de Lausanne. Samples together with standard minerals of known age were irradiated for 20 MWh in the central thimble position of the TRIGA reactor in Denver, CO (Dalrymple et al. 1981). Production ratios for the TRIGA reactor were determined from analyses of irradiated salts. The standard mineral MMHB-1 with an age of 520.4 Ma (Samson & Alexander 1987) was used to correct for the neutron flux, which was determined with an intra-sample precision of 0.5%. Samples were incrementally heated in a low blank, double vacuum resistance furnace and purified using activated Zr/Ti/Al getters and a cold finger maintained at liquid nitrogen temperatures. Blanks were measured at temperature and subtracted from the sample signal. For mass 40, blank values ranged from 4×10^{-15} moles below 1350 °C to 9×10^{-15} moles at 1650 °C. Blank values for masses 36–39 were below 2×10^{-17} moles for all temperatures. Seven scans per analysis were made over the mass range 40 to 36. Peak heights above backgrounds were corrected for mass discrimination, isotopic decay and interfering Ca-, K- und Cl-derived isotopes of argon.

5.b Results

Zircon characteristics and U-Pb data

Only large anhedral zircon fragments, up to 300 microns long, were recovered from the mineral separation of both analysed samples (MR3 and RB3). The crystals were transparent, lightly pink and devoid of inclusions. Three zircon fractions were selected from each sample for isotopic analysis (Tab. 2). All consisted of gem-quality, inclusion-free grains, non-magnetic at 1.6 A and 0° lateral tilt on the Frantz isodynamic separator. Very tiny cracks were present in a couple of selected grains. Fractions (1) to (6) included 2, 3, 8, 7, 8 and 22 fragments, respectively, with similar characteristics.

Isotopic data are reported in Table 2 and Figure 4. Fraction (4) revealed a few picograms of common Pb after correction for blank, as expressed by its low $^{206}Pb/^{204}Pb$ ratio of 375; a correction was made according to the Stacey & Kramers (1975) model at 166 Ma. All zircon fractions display low total Pb concentrations ranging between 1.6 and 9 ppm, and con-

Tab. 3. $^{40}Ar/^{39}Ar$ experimental data for the amphibole from gabbro MR3. All data in moles and indicate values above baselines corrected only for blanks, decay and mass discrimination. Ages are corrected for interferring Ca-, K-, and Cl-derived isotopes of argon, and include a 0.5% error on J.

MR3 Amphibole, wt. = 30.12 mg, J = 0.004789 ± 0.5%							
Temperature (°C)	$^{40}Ar \times 10^{-16}$	$^{39}Ar \times 10^{-18}$	$^{37}Ar \times 10^{-18}$	$^{36}Ar \times 10^{-19}$	^{39}Ar (% of tot)	%40Ar*	Age ± 2 s (Ma)
850	5661 ± 32	2642 ± 69	35360 ± 388	15229 ± 234	0.6	21	354.8 ± 112
950	3796 ± 15	2488 ± 57	41105 ± 357	8316 ± 128	0.5	36.1	426.6 ± 34.5
975	583 ± 1	1072 ± 16	17280 ± 96	887 ± 36	0.2	57.3	253.6 ± 8.2
1000	448 ± 1	1138 ± 16	25956 ± 219	614 ± 33	0.2	64	208.5 ± 5.8
1025	428 ± 1	1226 ± 17	30306 ± 175	804 ± 37	0.3	50	147.0 ± 8.1
1050	518 ± 1	1825 ± 23	31446 ± 191	890 ± 42	0.4	53.9	129.0 ± 8.2
1075	1050 ± 2	4539 ± 28	43777 ± 329	818 ± 37	1	80.2	154.5 ± 3.1
1100	3783 ± 10	17833 ± 71	126322 ± 722	1318 ± 53	3.8	92.3	162.4 ± 2.2
1150	23916 ± 33	115268 ± 172	773634 ± 778	4179 ± 40	24.8	97.4	167.3 ± 1.8
1175	26872 ± 156	130251 ± 1054	933831 ± 7709	3831 ± 44	28	98.5	168.3 ± 3
1200	20632 ± 36	102246 ± 177	723491 ± 5379	2945 ± 44	22	98.5	164.8 ± 1.8
1300	15555 ± 18	76934 ± 273	539600 ± 2827	2331 ± 63	16.6	98.3	164.7 ± 1.9
1400	1032 ± 2	5393 ± 34	35534 ± 204	434 ± 44	1.2	90.2	143.9 ± 2.1
1600	1828 ± 2	1311 ± 21	7796 ± 54	5583 ± 68	0.3	10.1	118.2 ± 22.6
Fuse	202 ± 1	197 ± 42	161 ± 51	535 ± 24	<0.1	21.9	184.4 ± 36.2

Plateau age (1150-1300°C) = 165.9 ± 2.2 Ma
Total fusion age = 168.5 Ma

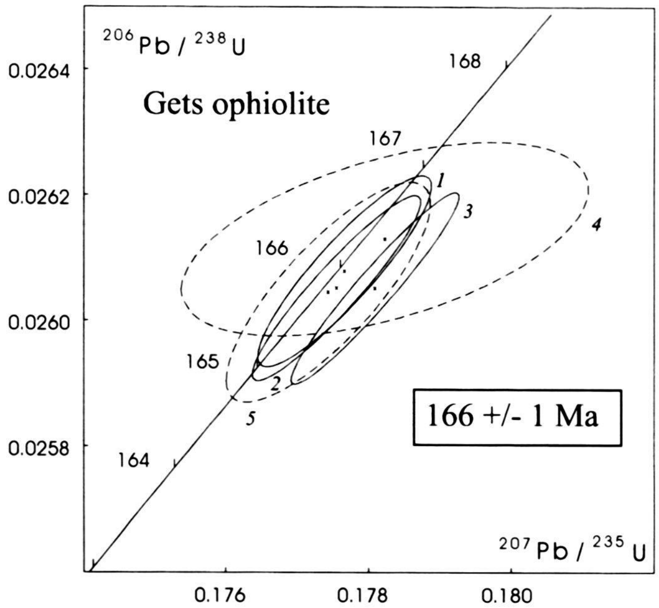


Fig. 4. U-Pb concordia diagram for zircons from gabbros MR3 and RB3. Ellipses are two sigma errors. Numbers refer to the zircon fractions listed in Tab. 1. Ellipses 1, 2, 3 relate to sample MR3, dashed ellipses (4,5) to sample RB3.

trasting U values of 120 to 300 ppm for MR3 and 58 to 77 ppm for RB3. Two fractions of each sample (1 and 2 from MR3; 4 and 5 from RB3) yielded identical concordant U-Pb ages ranging between 165.8 ± 0.8 and 166.4 ± 1.8 Ma. Conversely, fraction (6) is 30% discordant with a $^{207}Pb/^{206}Pb$ age of 336 Ma (not shown on Fig. 4), which most probably reflects the presence of an inherited lead component. Fraction (3), which displays rather high U (295 ppm), Pb (9 ppm) and model Th (342 ppm) contents compared to the other ones, is also slightly discordant (5.5%), a fact which might reflect either a small inheritance or an analytical problem. Considering the relatively young age of the analysed zircons, U-Pb ages will be preferred to Pb-Pb ones. As two fractions from each of the two samples yield the same concordant result within error, a mean Pb/U zircon age of 166 ± 1 Ma is proposed for these gabbro blocks of the Gets nappe. This age is interpreted as the crystallization age of the intrusive material, as no metamorphic overprint has been recorded in the latter.

$^{40}Ar/^{39}Ar$ results

The results of the $^{40}Ar/^{39}Ar$ step heating experiment for amphibole MR3 are shown in Table 3 and Figure 5. The argon was evolved at relatively high temperature steps, which is consistent with magnesium rich amphiboles (Lee 1993). Four high temperature steps between 1150° and 1300 °C, and comprising 90% of the ^{39}Ar released gave an age of 165.9 ± 2.2 Ma (2σ). Using the plateau steps, an $^{36}Ar/^{40}Ar$ vs $^{39}Ar/^{40}Ar$ isochron age of 161.9 ± 2.3 Ma (2σ) is calculated. However, these heating steps are clustered on this isochron, resulting in poorly constrained values for the age and trapped $^{40}Ar/^{36}Ar$. The greater than atmospheric value of trapped $^{40}Ar/^{36}Ar$ (655 ± 141) could indicate the presence of some excess argon, but the poor regression statistics make this assumption equivocal. The low K/Ca and K/Cl ratios observed in the lower temperature steps are consistent with outgassing of small concentrations of low K alteration products, perhaps chlorite.

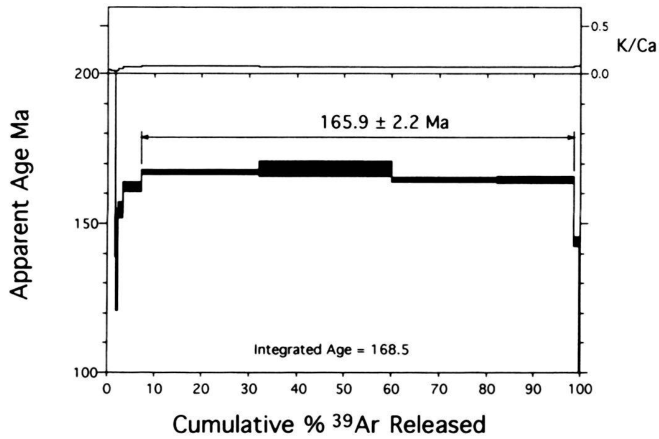
6. Age of Piemont ophiolites and implications for alpine tectonics

We observe a remarkable agreement between several sets of data:

- The $^{40}Ar/^{39}Ar$ amphibole age and the U-Pb zircon age of gabbro MR3. This concordance implies that 166 ± 1 Ma is the age of magmatic crystallization of the gabbro. It falls into the late part of the Bajocian stage (170 to 164 Ma according to the time scale of Odin 1994).
- The U-Pb ages of both analysed samples. As they come from different localities, this is a hint to the age homogeneity of the ophiolitic rocks from the Gets nappe. However it is clear that more analyses are needed before we can consider this point as demonstrated.
- The isotopic age of the Gets gabbros and the opening age of the Piemont ocean as inferred from the geology of its NW Briançonnais margin (cf 3.c). This temporal coincidence not only confirms the coherence of the interpretation proposed above and the Piemont origin of the Gets ophiolites, but, if systematically confirmed by the anlyses of more samples, it would further imply that the Gets ophiolites belong to the earliest preserved oceanic crust generated during the birth of the Piemont ocean. This is indeed in agreement with the proposed homeland of the Gets nappe at the foot of the southern continental margin: it is in this very part of the accretionary prism that we should expect to find the oldest portions of the oceanic crust scraped off the subducting lithosphere.

This interpretation would mean that the rupture of the continental crust happened 10 to (more probably) 20 Ma after the initiation of the Briançonnais doming (depending on the uncertainties about the onset of its uplift, see 3.c). This time span is comparable to the chronology observed in younger, well preserved rifts evolving towards oceanization, such as the Red Sea (e.g. Bonatti 1988, Favre & Stampfli 1992, Omar & Steckler 1995). The triple coincidence, within the limits of stratigraphic constraints, between the end of tensile fracturing in the Briançonnais continental crust, the beginning of its subsidence, and the age of the Gets ophiolites, is particularly remarkable with respect to models of ocean opening based on a combination of subhorizontal extension and thermally driven vertical movements of the lithosphere. It is well known from classical stress theory (Hafner 1951) that rupture of the crust by extension and low angle listric normal faulting (or simple shear) can only result from the superposition of a subhorizontal basal shearing stress and a strong component of vertical normal stress (caused by an asthenospheric uplift). The timing of the structural evolution of the Briançonnais rise, the 160 ± 8 Ma cooling age of the mantle-derived Totalp ultramafic body (Peters & Stettler 1987), and the 166 ± 1 Ma crystallization age of the Gets ophiolites all fit well into a geodynamic scenario of this type.

As a consequence of this interpretation, younger ages could be found in the ophiolitic bodies of the Tsaté nappe which probably represents a more distal part of the prism. The biostratigraphy of the supra-ophiolitic radiolarites in the Alps and the northern Apennines seems to indicate that sea-floor spreading of the Piemont ocean and its probable southern (Ligurian) continuation lasted at least 20 Ma. The 161 ± 3 Ma age



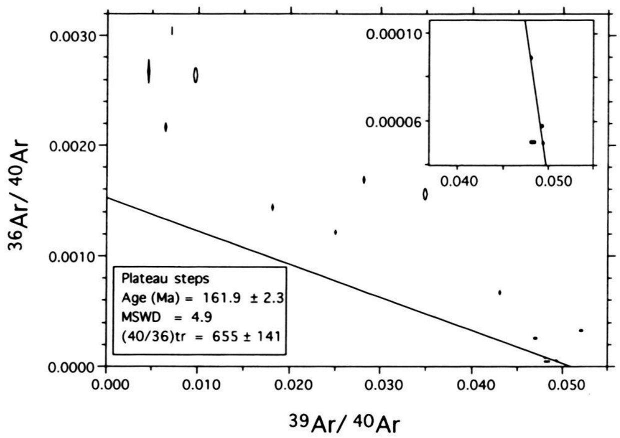


Fig. 5. $^{40}Ar/^{39}Ar$ age spectrum and isochron of the amphibole from gabbro MR3. Error ellipses on isochron are 1 sigma.

of a Corsican ophiolite (Ohnenstetter et al. 1981), as well as the ages around 150 or 158 Ma found in some Apenninic ophiolites (Borsi 1995, Bortolotti et al. 1995) fall into this range.

Acknowledgements

This work has been partly supported by the Swiss National Science Foundation (projects 20-40756.94 and 21-45789.95). The chemical analyses of the gabbros have been done at the Centre d'analyse minérale (Université de Lausanne). We thank J. Hernandez for his help in the interpretation of the chemistry. We sincerely thank G. V. Dal Piaz (Padova) and I. Villa (Bern) for a stimulating review of the manuscript. F. B. is indebted to T. Krogh and D. Davis, Royal Ontario Museum, for the use of the geochronological laboratory.

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Manuscript received June 3, 1996
Revision accepted September 26, 1996